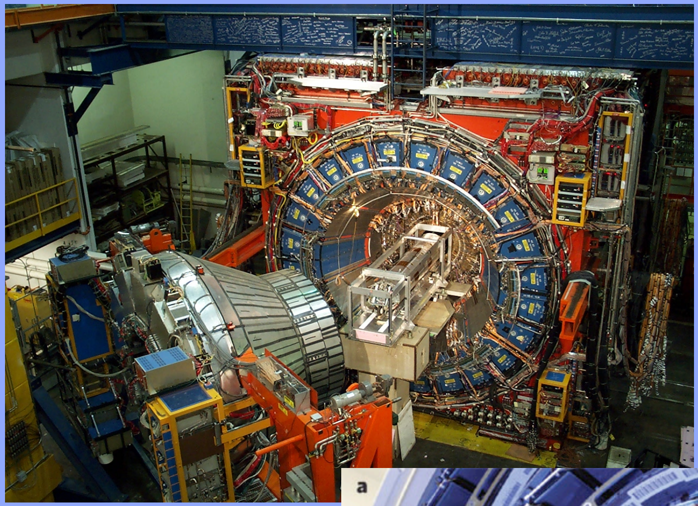
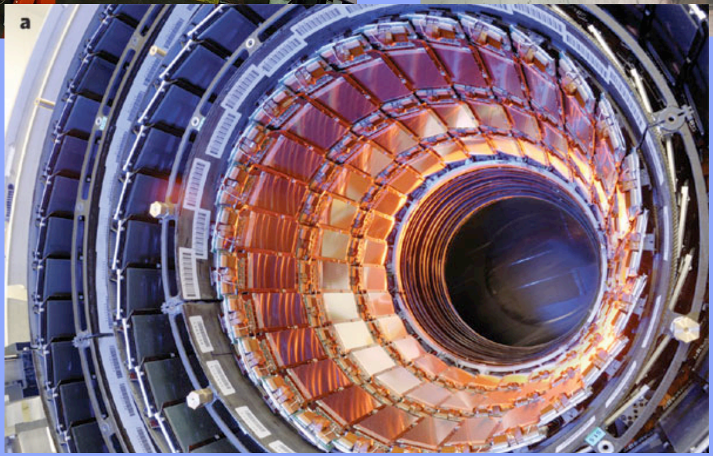
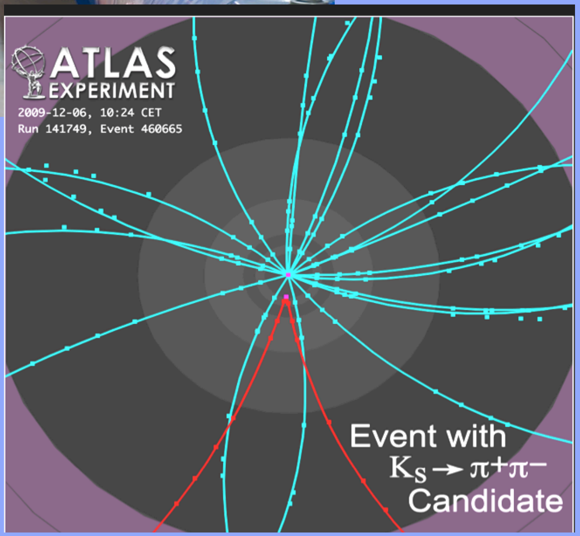
Particle Physics from Tevatron to LHC: what we know and what we hope to discover







Beate Heinemann, UC Berkeley and LBNL

Università di Pisa, February 2010

Outline

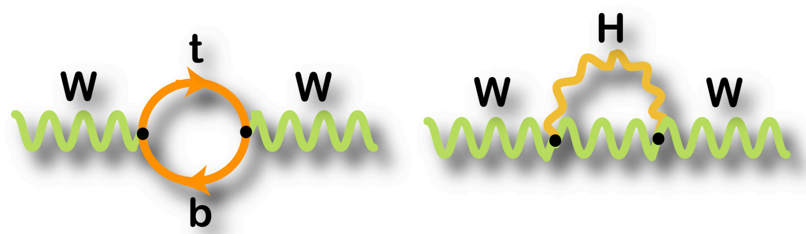
- **Introduction**
  - Outstanding problems in particle physics
    - and the role of hadron colliders
  - Current and near future colliders: Tevatron and LHC
- **Standard Model Measurements**
  - Hadron-hadron collisions
  - Cross Section Measurements of jets, W/Z bosons and top quarks
- **Constraints on and Searches for the Higgs Boson**
  - W boson and Top quark mass measurements
  - Standard Model Higgs Boson
- **Searches for New Physics**
  - Supersymmetry
  - Higgs Bosons beyond the Standard Model
  - High Mass Resonances (Extra Dimensions etc.)
- **First Results from the 2009 LHC run**

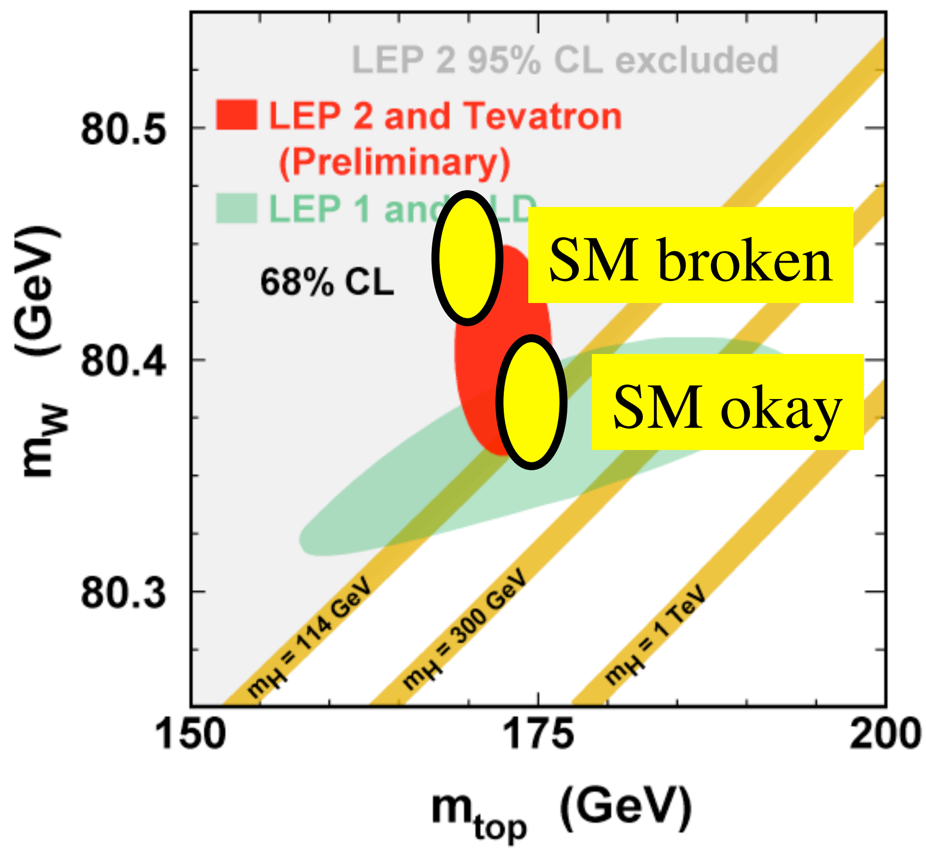
Precision Measurement of Electroweak Sector of the Standard Model

- W boson mass
- Top quark mass
- Implications for the Higgs boson

The W boson, the top quark and the Higgs boson

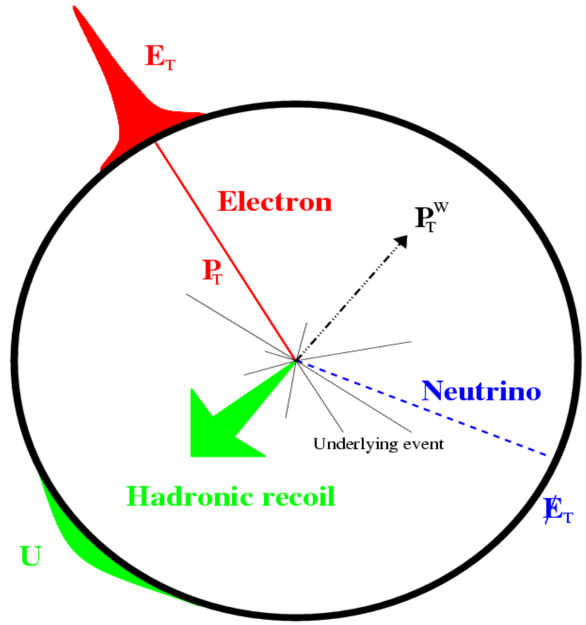
- Top quark is the heaviest known fundamental particle
  - Today: m_{top}=173.1+-1.3 GeV
  - Run 1: m_{top}=178+-4.3 GeV/c^2
  - Is this large mass telling us something about electroweak symmetry breaking?
    - Top yukawa coupling:
    - $\langle H \rangle/(\sqrt{2}\, mtop) = 1.005 \pm 0.008$
- Masses related through radiative corrections:
  - $m_W \sim M_{top}^2$
  - $m_W \sim \ln(m_H)$
- If there are new particles the relation might change:
  - Precision measurement of top quark and W boson mass can reveal new physics





W Boson mass

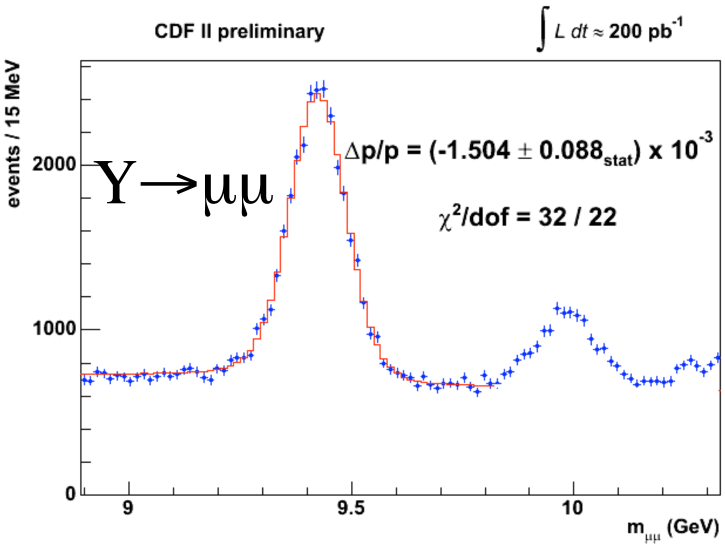
- Real precision measurement:
  - LEP: M_W=80.367±0.033 GeV/c^2
  - Precision: 0.04%
    - => Very challenging!
- Main measurement ingredients:
  - Lepton p_T
  - Hadronic recoil parallel to lepton: $u_{||}$
- Z→ll superb calibration sample:
  - but statistically limited:
    - About a factor 10 less Z's than W's
    - Most systematic uncertainties are related to size of Z sample
      - Will scale with $1/\sqrt{N_Z}$ $(=1/\sqrt{L})$

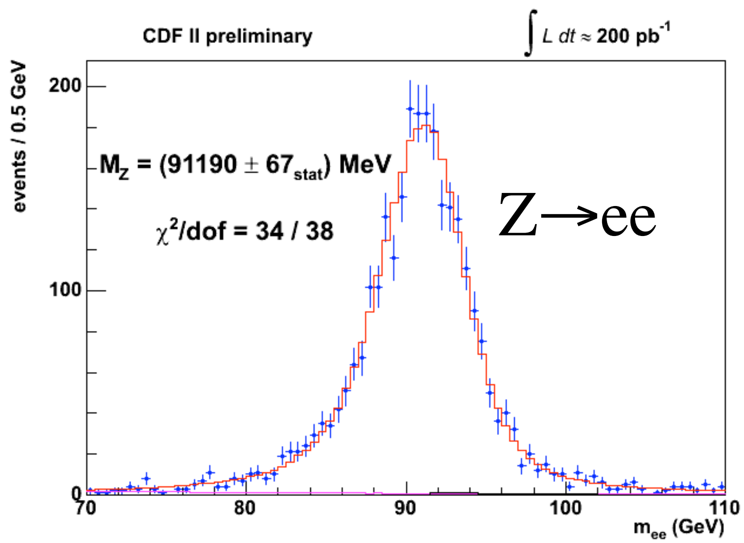


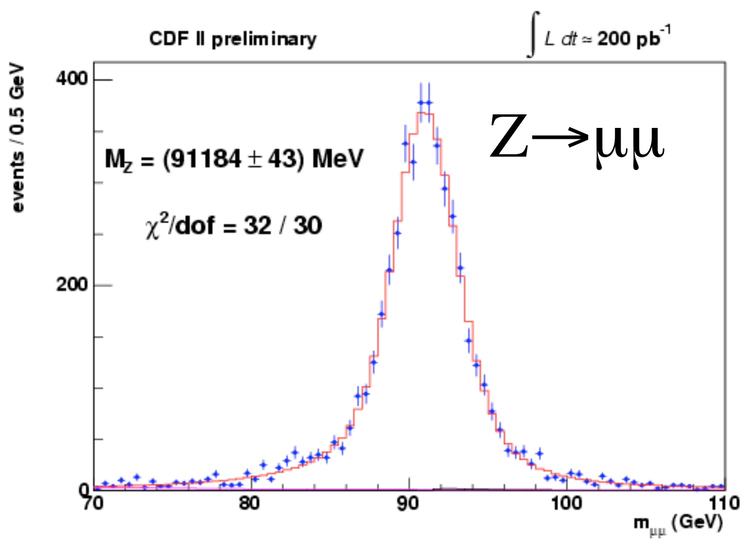
$$m_T = \sqrt{2 p_T^l \not{p}_T \,(1-\cos\Delta\phi)},$$
$$\not{p}_T \approx |p_T + u_{||}|$$

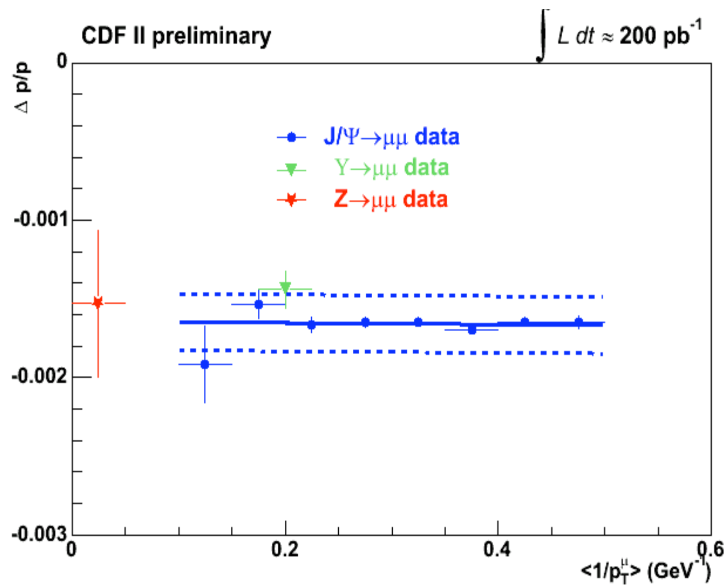
$$m_T \approx 2p_T\sqrt{1+u_{||}/p_T} \approx 2p_T + u_{||}$$

Lepton Momentum Scale and Resolution









- **Systematic uncertainty on momentum scale: 0.04%**

Systematic Uncertainties

m_T Fit Uncertainties			
Source	$W \to \mu\nu$	$W \to e\nu$	Correlation
Tracker Momentum Scale	17	17	100%
Calorimeter Energy Scale	0	25	0%
Lepton Resolution	3	9	0%
Lepton Efficiency	1	3	0%
Lepton Tower Removal	5	8	100%
Recoil Scale	9	9	100%
Recoil Resolution	7	7	100%
Backgrounds	9	8	0%
PDFs	11	11	100%
W Boson p_T	3	3	100%
Photon Radiation	12	11	100%
Statistical	54	48	0%
Total	60	62	-

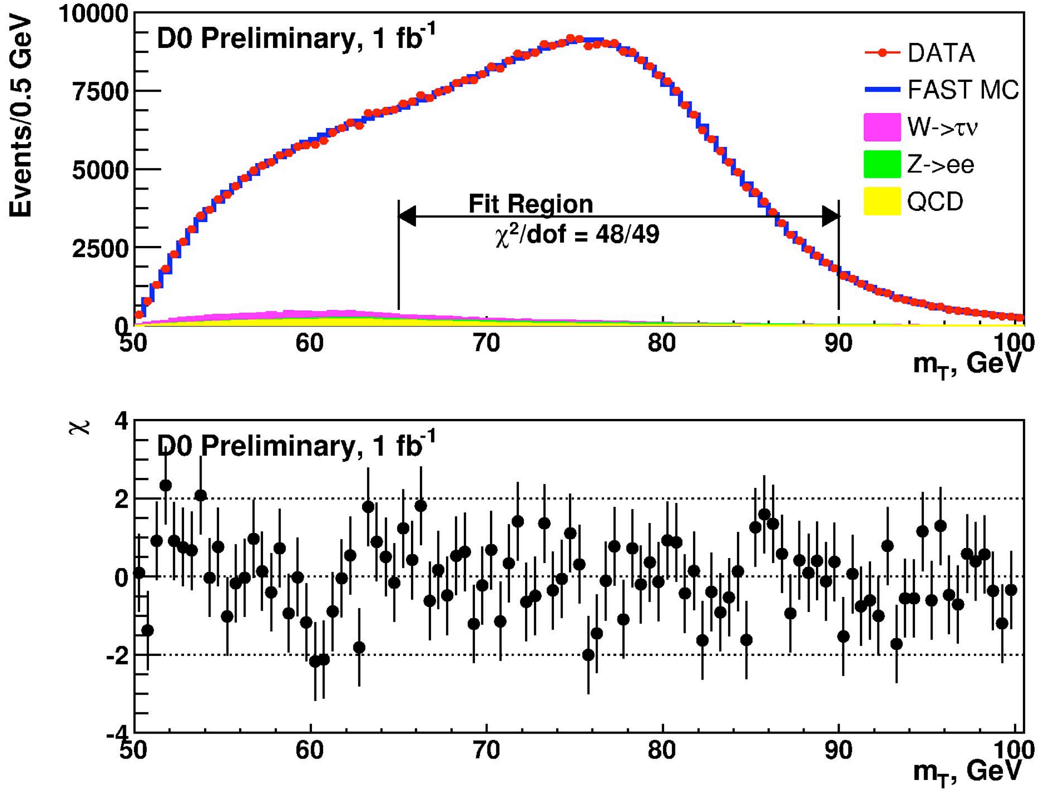
Limited by data statistics

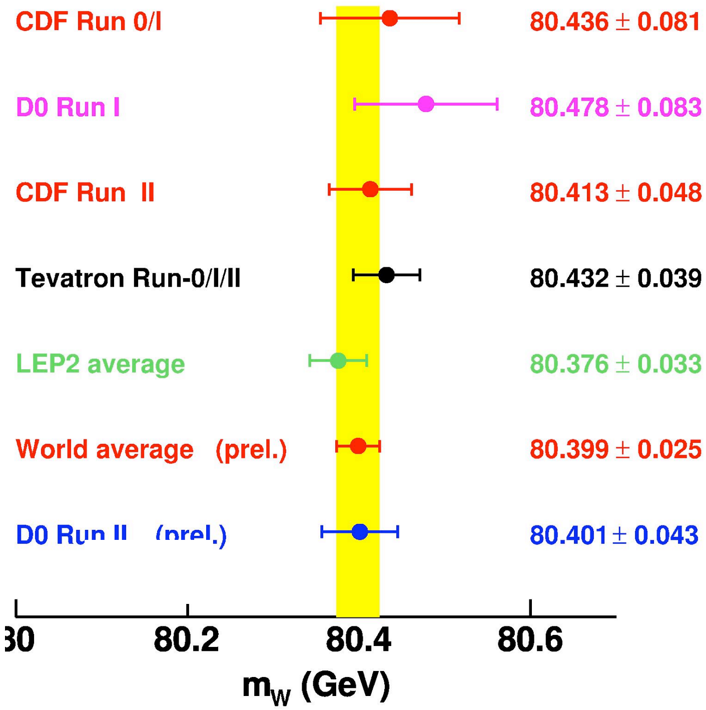
Limited by data and theoretical understanding

TABLE IX: Uncertainties in units of MeV on the transverse mass fit for m_W in the $W \to \mu\nu$ and $W \to e\nu$ samples.

- Overall uncertainty 60 MeV for both analyses
  - Careful treatment of correlations between them
- Dominated by stat. error (50 MeV) vs syst. (33 MeV)

W Boson Mass





New world average:

M_W=80399 ± 23 MeV

Ultimate precision:

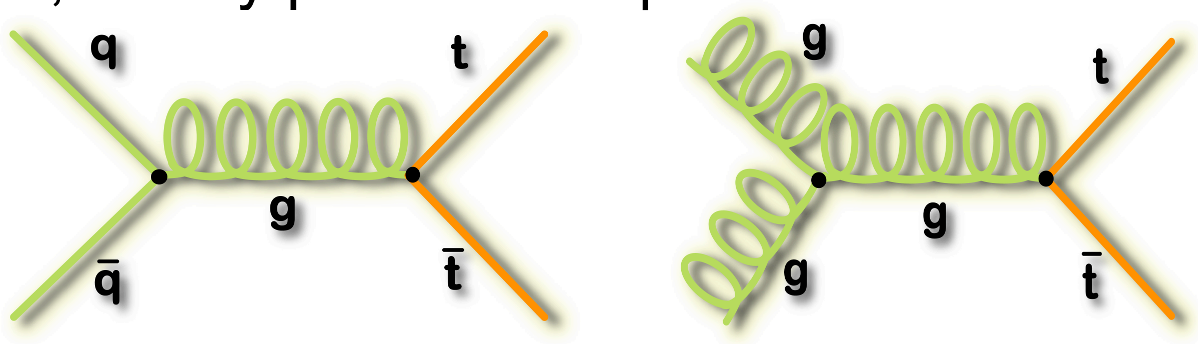
Tevatron: 15-20 MeV

LHC: unclear (5 MeV?)

Top Quark Production and Decay

- At Tevatron, mainly produced in pairs via the strong interaction

85%



15%

- Decay via the electroweak interactions **Br(t →Wb) ~ 100%**
  Final state is characterized by the decay of the W boson

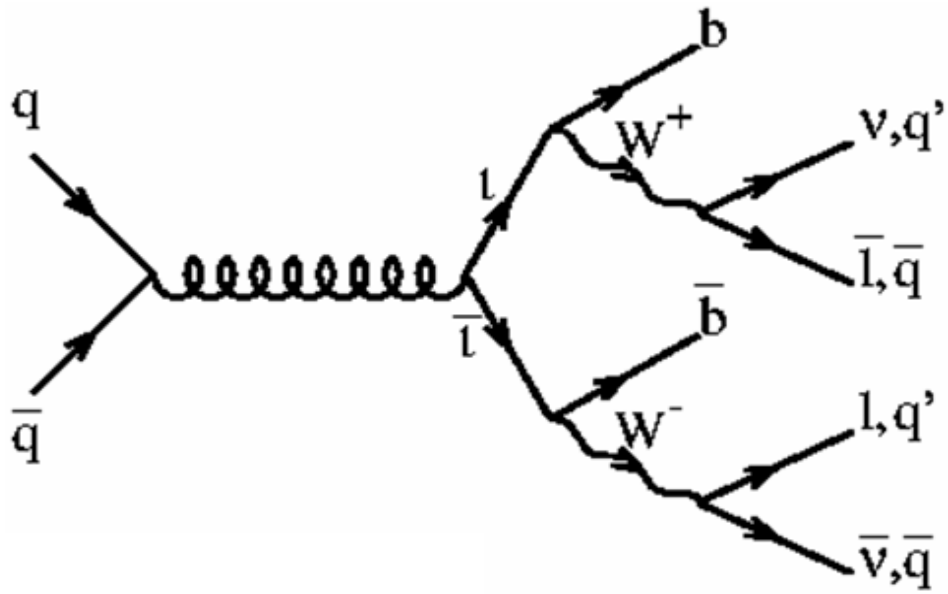
- Cross Sections at Tevatron and LHC:
  - Tevatron: 7 pb
  - LHC (7 TeV): 160 pb
  - LHC (10 TeV): 400 pb
  - LHC (14 TeV): 890 pb

How to identify the top quark

SM: $t\bar{t}$ pair production, Br($t \rightarrow bW$)=100% , Br($W \rightarrow l\nu$)=1/9=11%

dilepton	***(4/81)***	**2 leptons + 2 jets + missing E_T**
l+jets	***(24/81)***	**1 lepton + 4 jets + missing E_T**
fully hadronic	***(36/81)***	**6 jets**

(here: l=e,μ)



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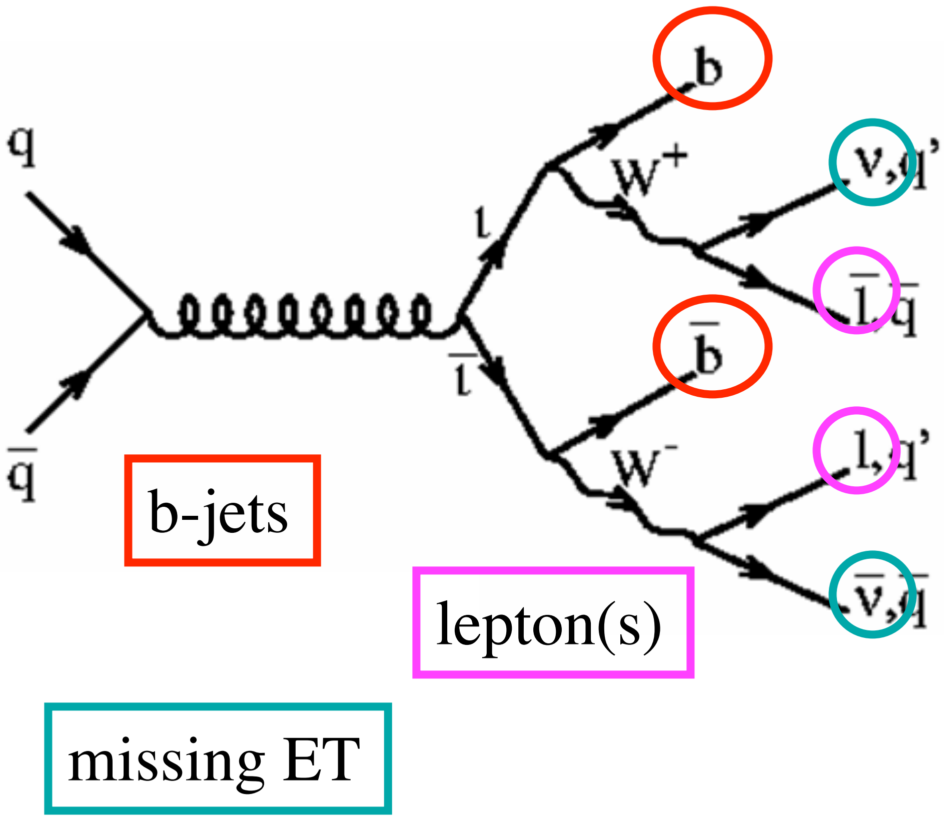

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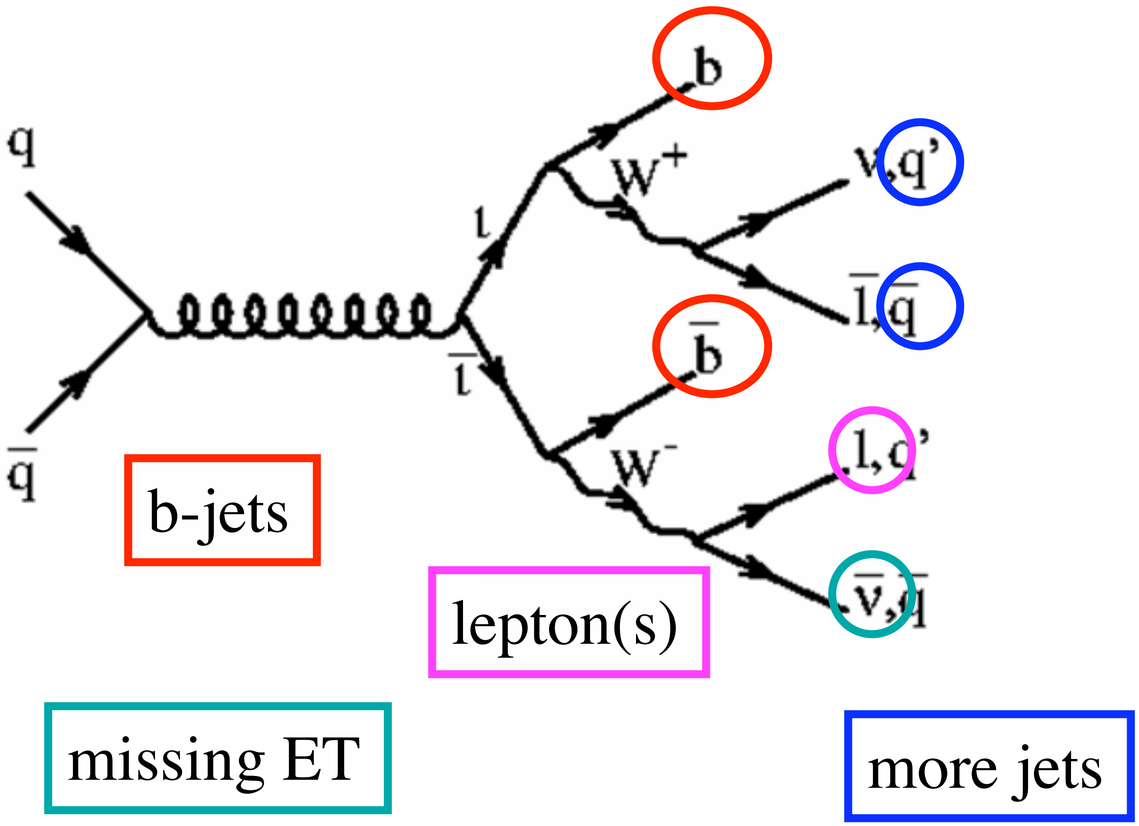

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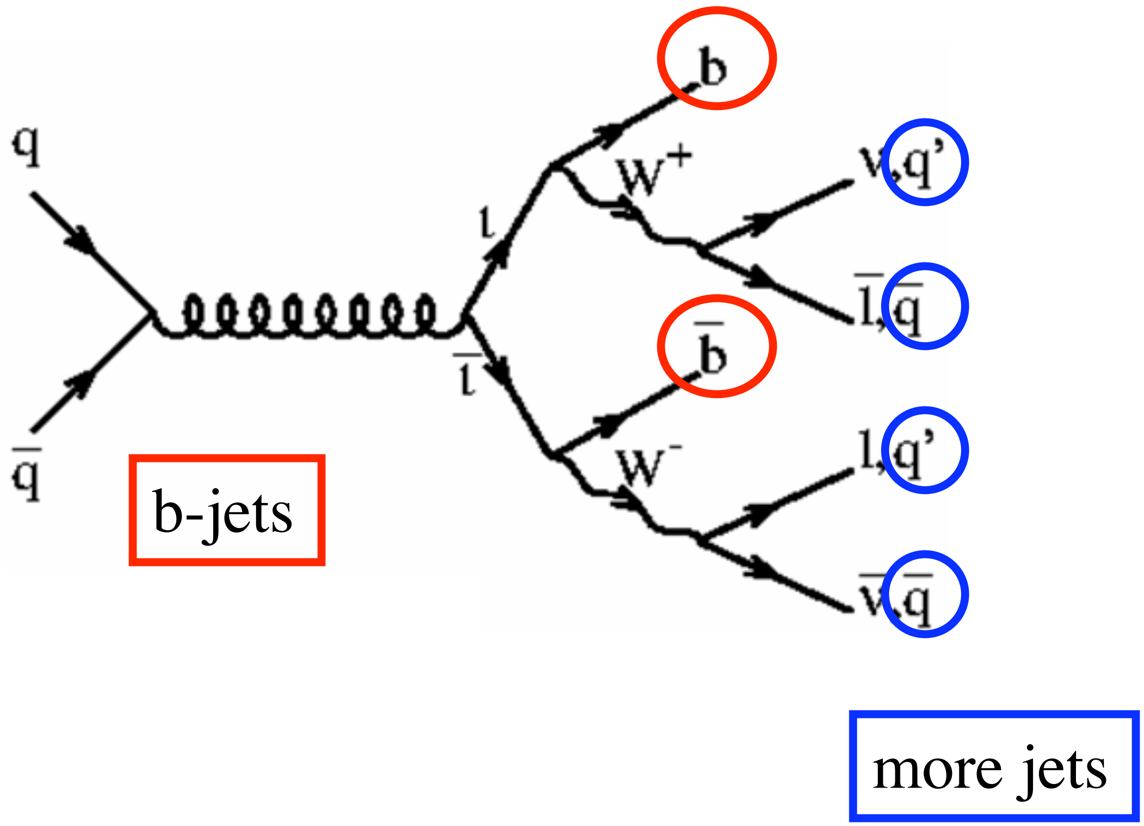
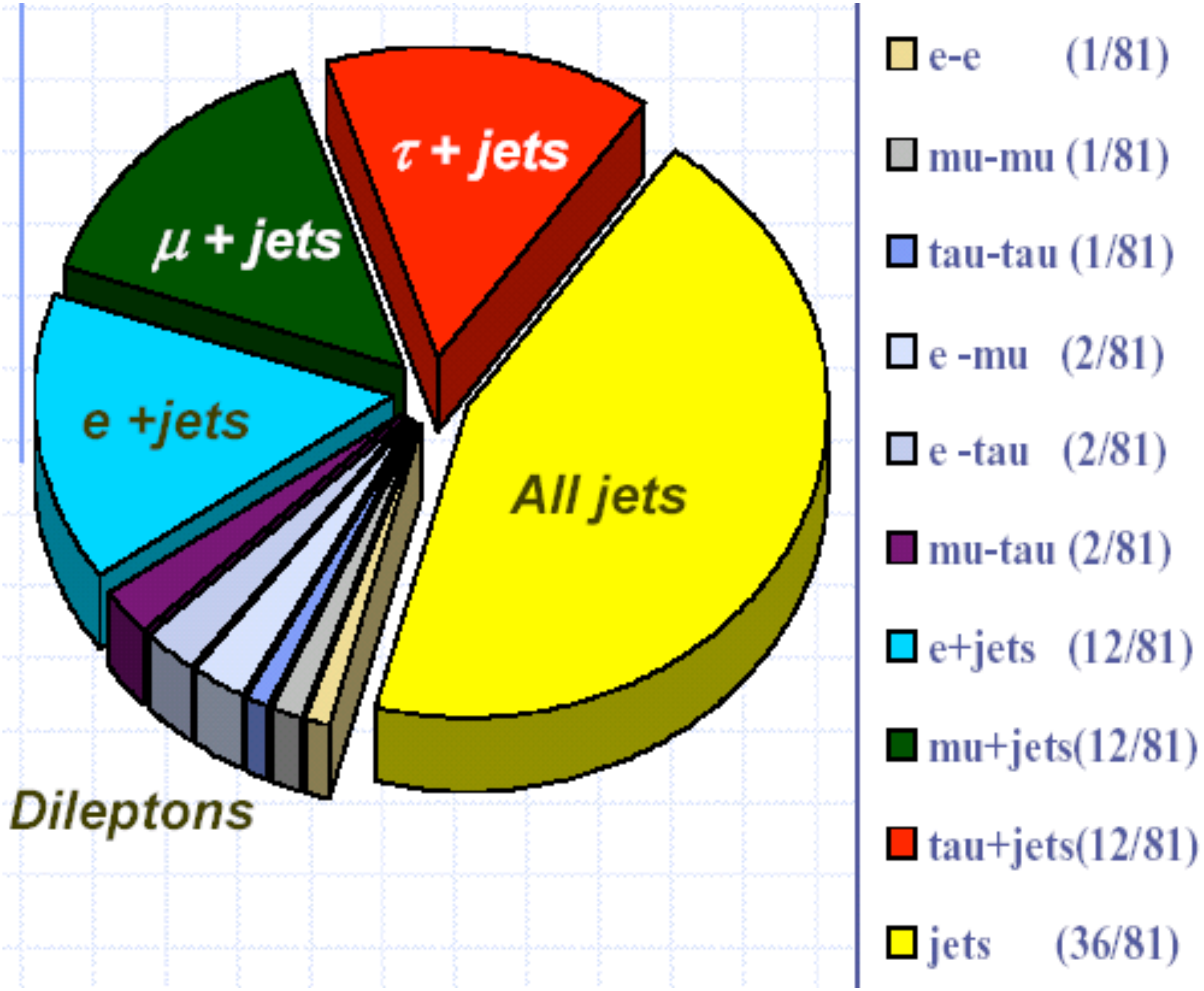
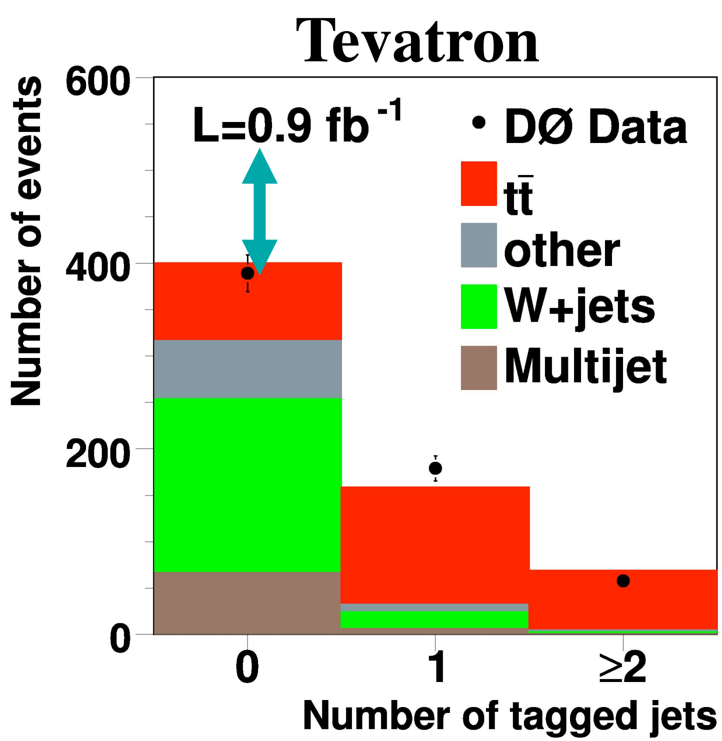
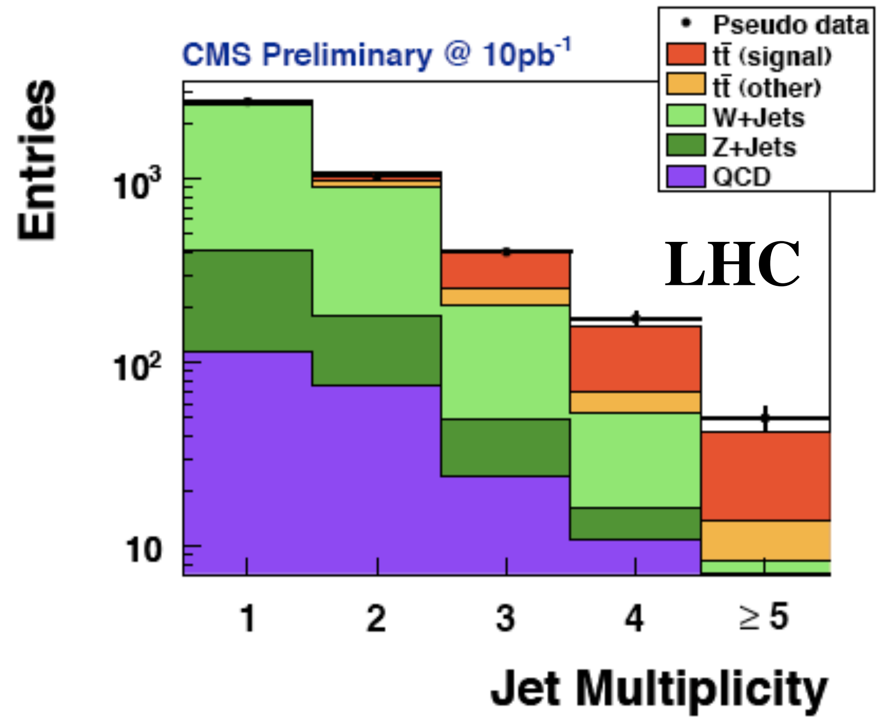


Top Event Categories



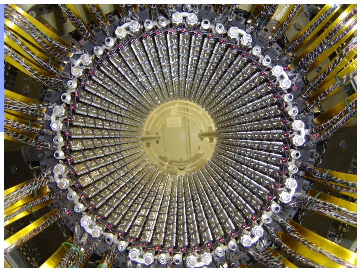
Finding the Top at Tevatron and LHC without b-quark identification



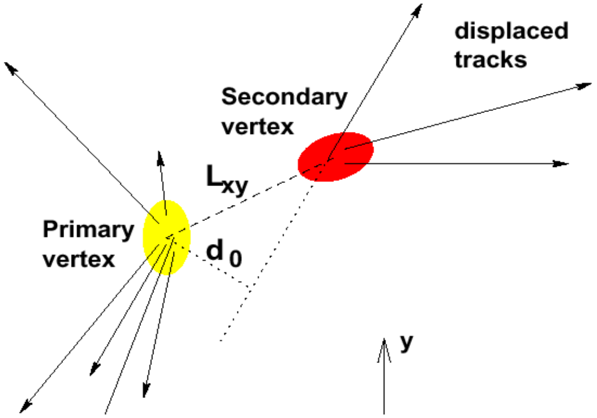


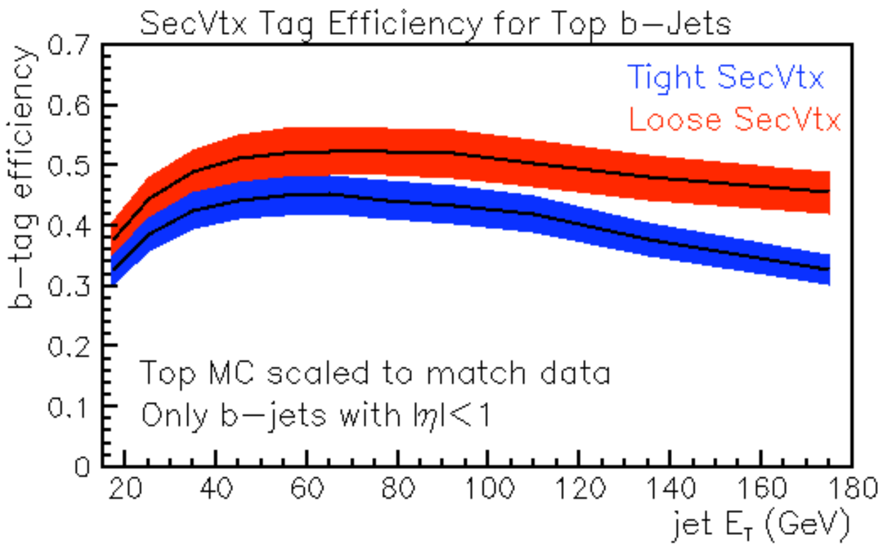
- Tevatron:
  - Top is overwhelmed by backgrounds:
  - Even for 4 jets S/B is only about 0.8
  - Use b-jets to purify sample
- LHC
  - Signal clear even without b-tagging: S/B is about 1.5-2

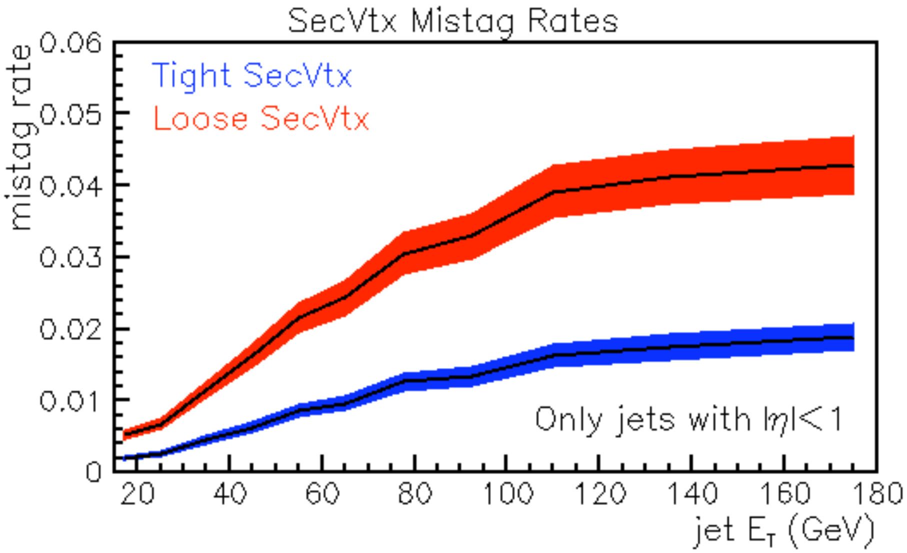
Finding the b-jets



- Exploit large lifetime of the b-hadron
  - B-hadron flies before it decays: d=cτ
    - Lifetime τ =1.5 ps^{-1}
    - d=cτ = 460 μm
    - Can be resolved with silicon detector resolution

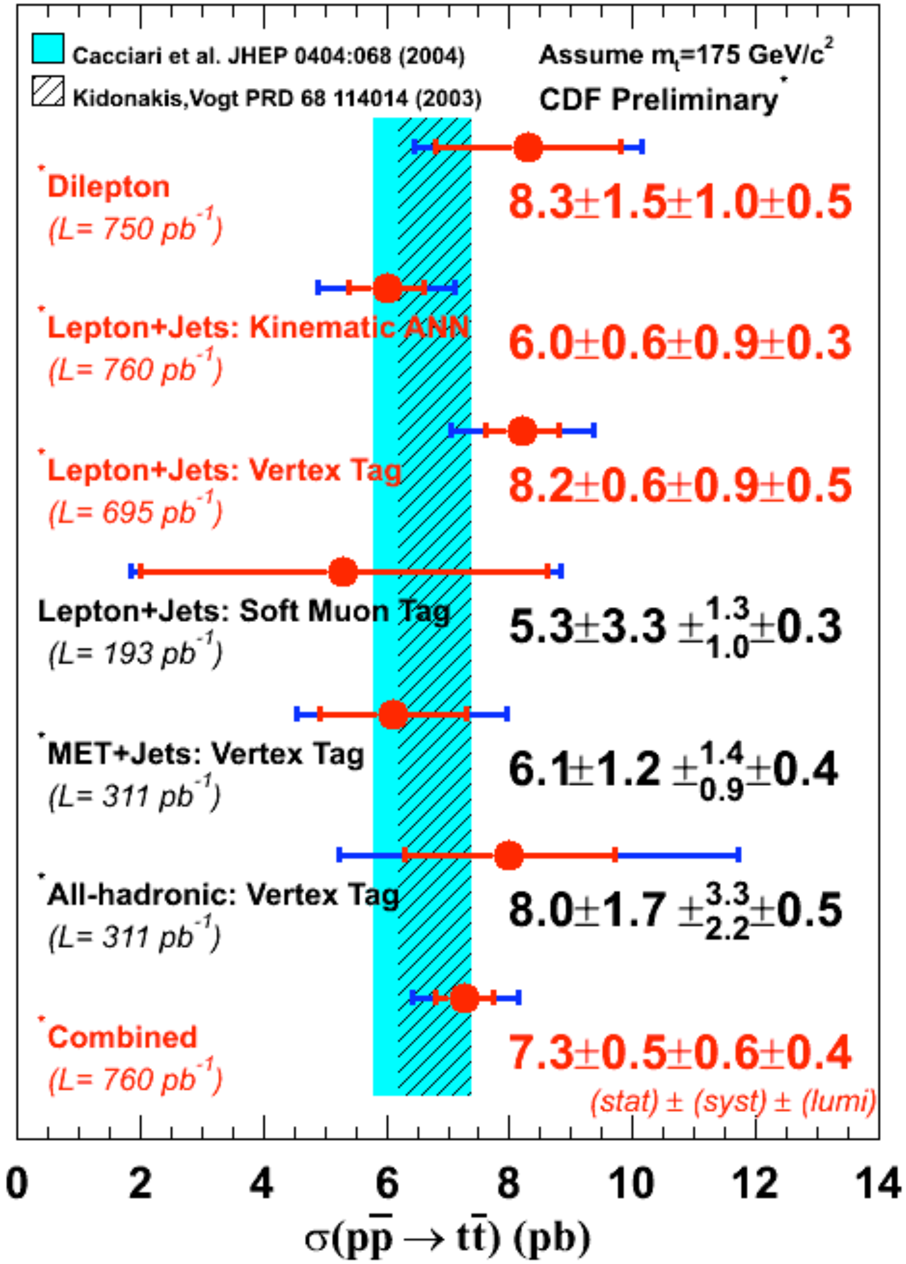






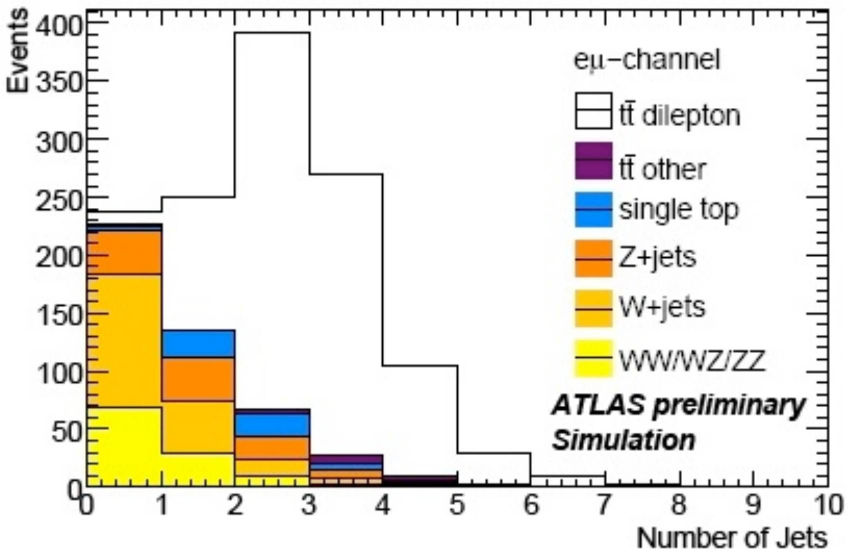
Achieve efficiency of about 40-50% and fake rate of 0.5-2% (at 50 GeV) at Tevatron

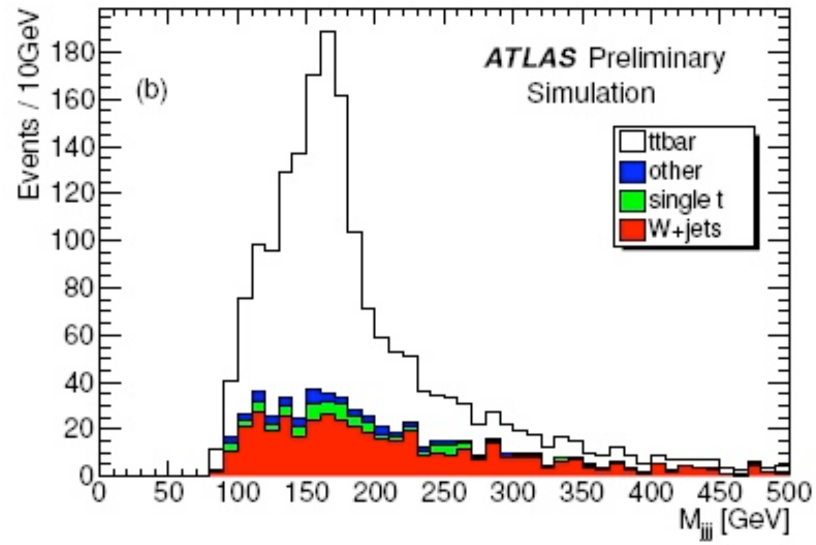
The Top Cross Section



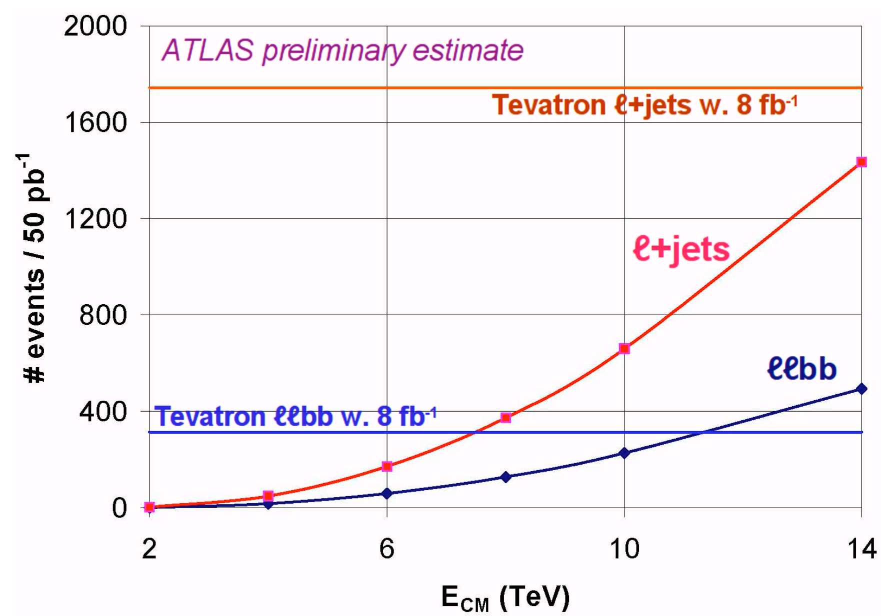
- **Tevatron**
  - Measured using many different techniques
  - Good agreement
    - between all measurements
    - between data and theory
  - Precision: ~13%
- **LHC:**
  - Cross section ~100 times larger
  - Measurement will be one of the first milestones (already with 10 pb^{-1})
    - Test prediction
    - demonstrate good understanding of detector
  - Expected precision
    - ~4% with 100 pb^{-1}

Top at LHC: very clean



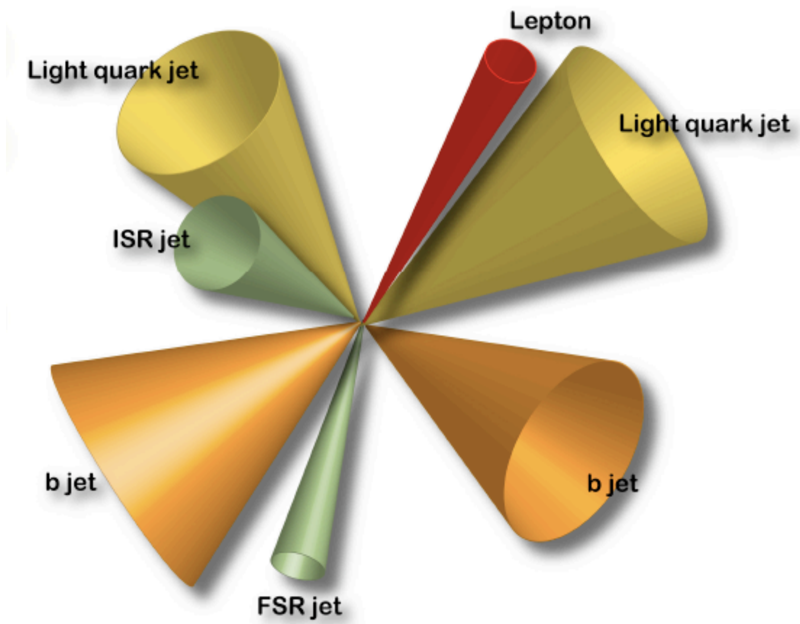


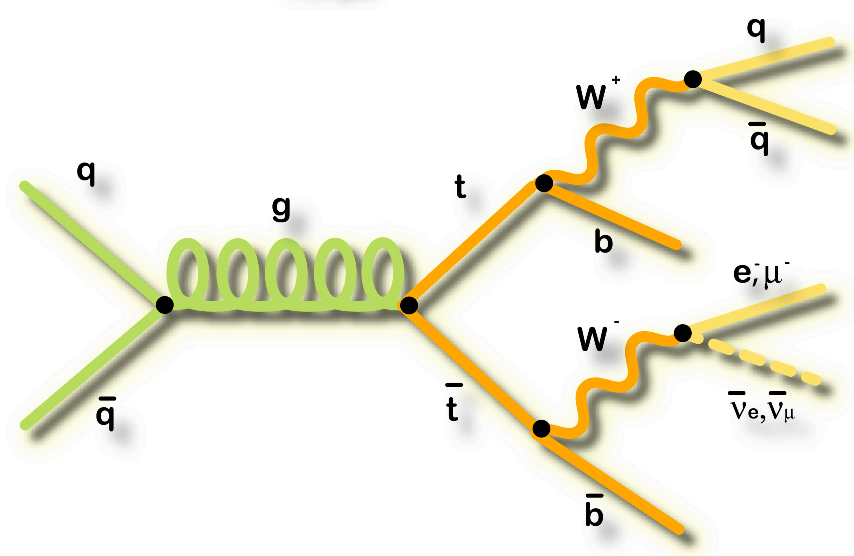
- At √s=7 TeV:
  - About 200 pb^{-1} surpass Tevatron top sample statistics
  - About 20 pb^{-1} needed for "rediscovery"



Top Mass Measurement: $tt \rightarrow (bl\nu)\,(bqq)$

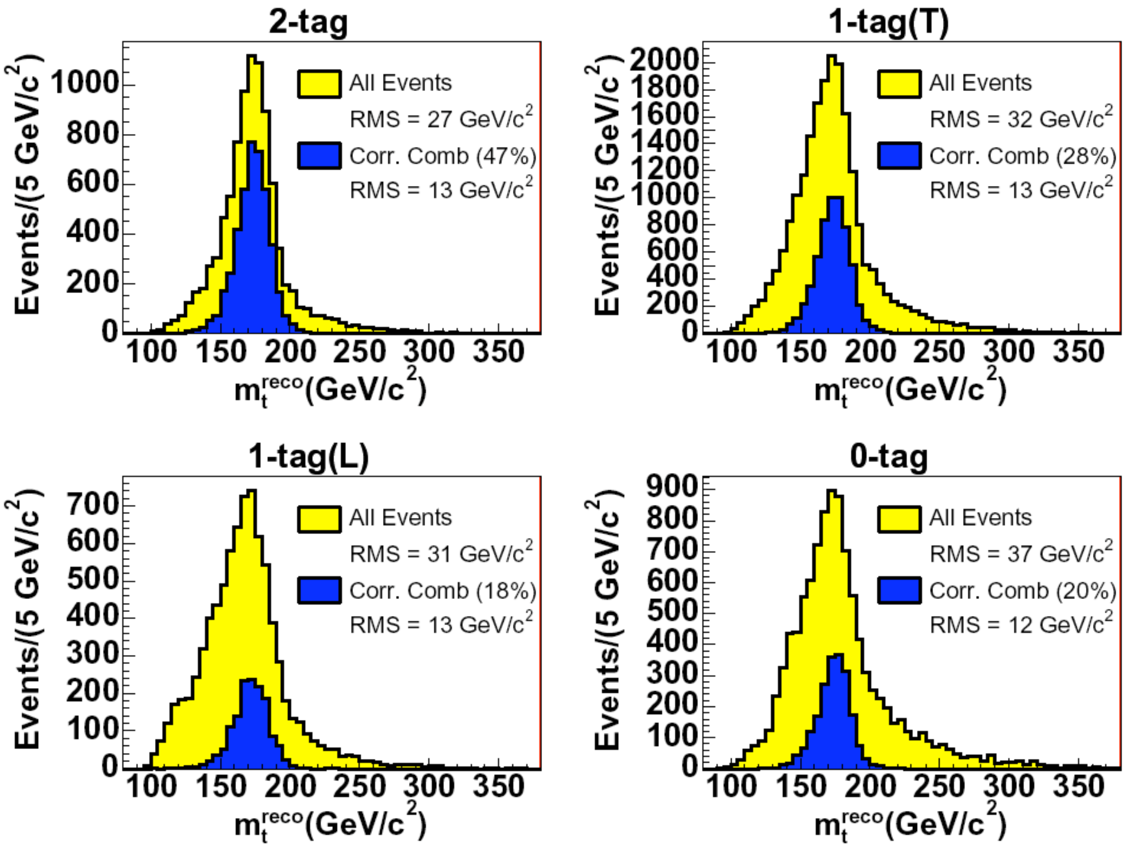
- 4 jets, 1 lepton and missing E_T
  - Which jet belongs to what?
  - Combinatorics!
- B-tagging helps:
  - 2 b-tags =>2 combinations
  - 1 b-tag => 6 combinations
  - 0 b-tags =>12 combinations
- Two Strategies:
  - Template method:
    - Uses “best” combination
    - Chi2 fit requires $m(t)=m(\bar{t})$
  - Matrix Element method:
    - Uses all combinations
    - Assign probability depending on kinematic consistency with top





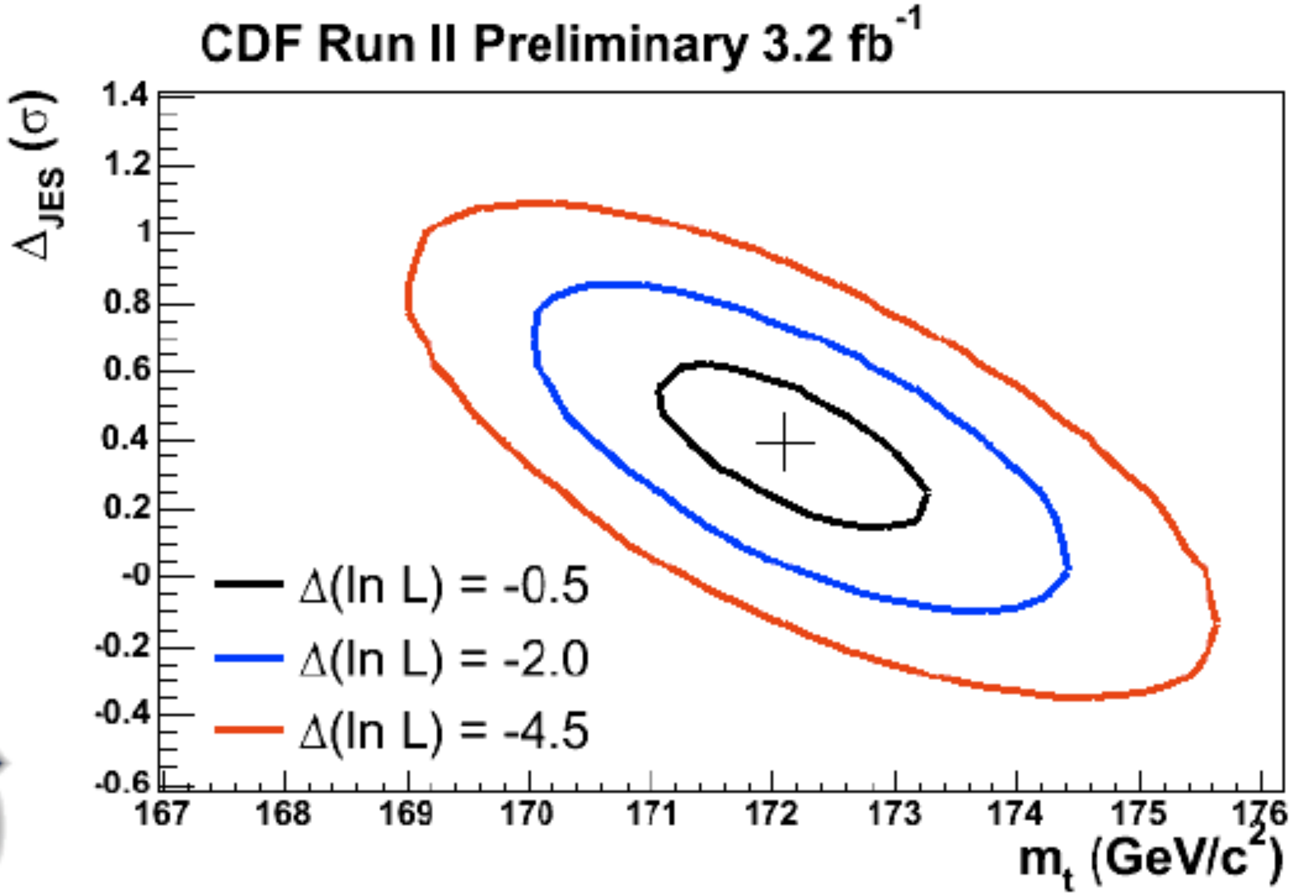
Top Mass Determination

- Inputs:
  - Jet 4-vectors
  - Lepton 4-vector
  - Remaining transverse energy, $p_{T,UE}$:
    - $p_{T,\nu}=-(p_{T,l}+p_{T,UE}+\sum p_{T,jet})$
- Constraints:
  - $M(l\nu)=M_W$
  - $M(q\overline{q})=M_W$
  - $M(t)=M(\overline{t})$
- Unknown:
  - Neutrino p_z
- 1 unknown, 3 constraints:
  - Overconstrained
  - Can measure M(t) for each event: m_t^{reco}
  - Leave jet energy scale ("JES") as free parameter



Selecting correct combination 20-50% of the time

Example Results on m_{top}



m_{top} = 173.7 ± 0.8 (stat) ± 1.6 (syst) GeV

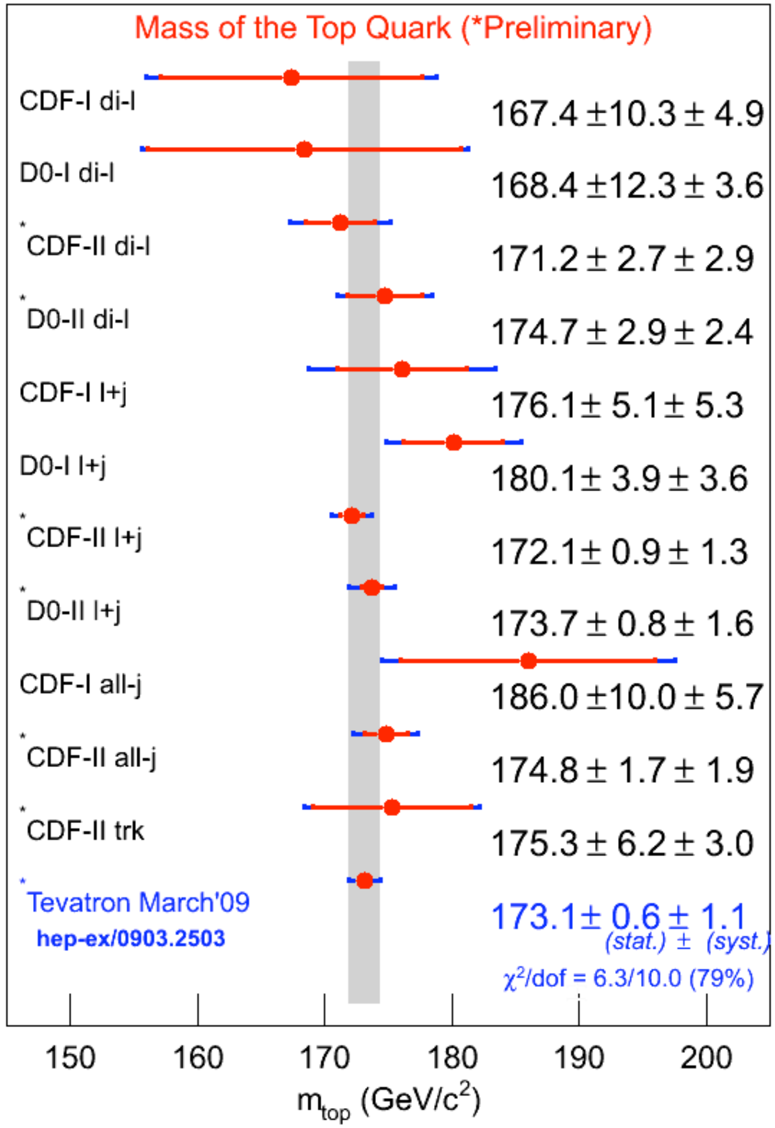
3.6 fb^{-1} ±1.0%

m_{top} = 172.1 ± 0.9 (stat) ± 1.3 (syst) GeV

3.2 fb^{-1} ±0.9%

Combining M_{top} Results

- Excellent results in each channel
  - Dilepton
  - Lepton+jets
  - All-hadronic
- Combine them to improve precision
  - Include Run-I results
  - Account for correlations
- **Uncertainty: 1.3 GeV**
  - Dominated by syst. uncertainties
- Precision so high that theorists wonder about what it's exact definition is!

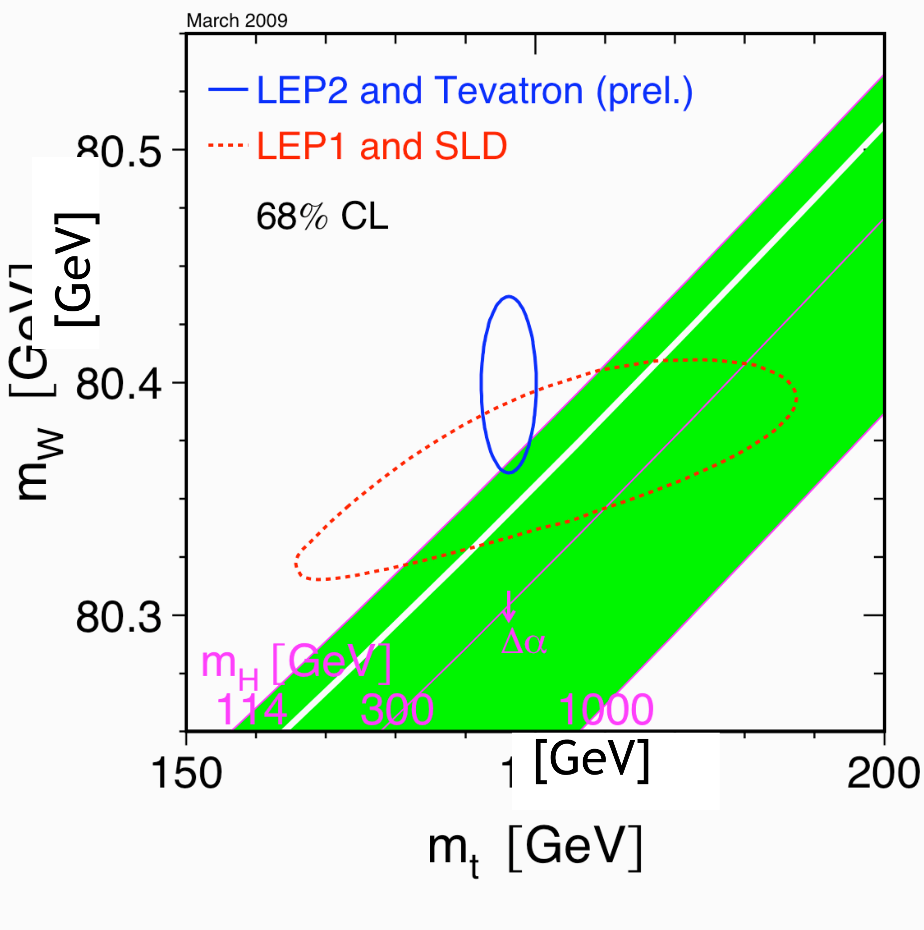


Tevatron/LHC expect to improve precision to ~1 GeV

Implications for the Higgs Boson

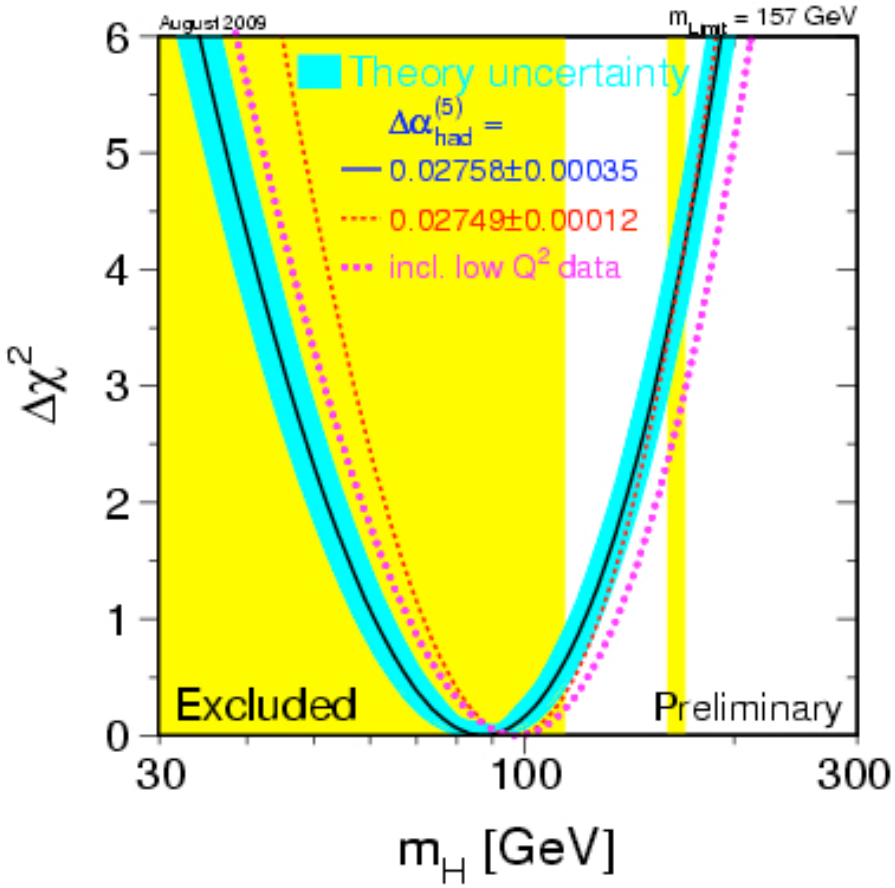
LEPEWWG 03/09

Relation: M_W vs m_{top} vs M_H



Standard Model still works!

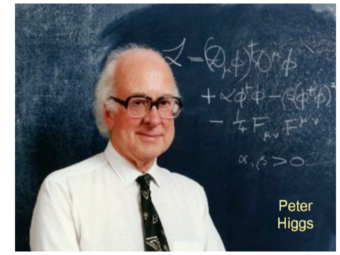
$m_H = 87^{+35}_{-26}$ GeV



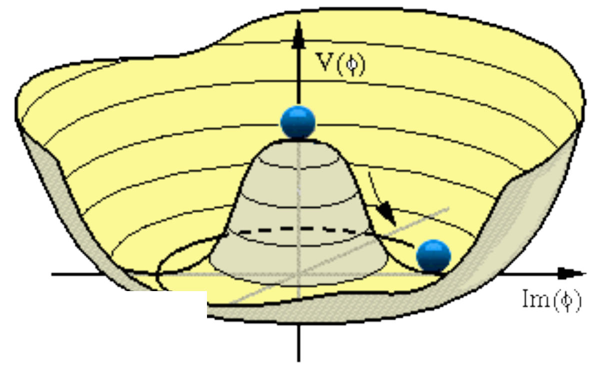
Indirect constraints:
m_H<163 GeV @95%CL

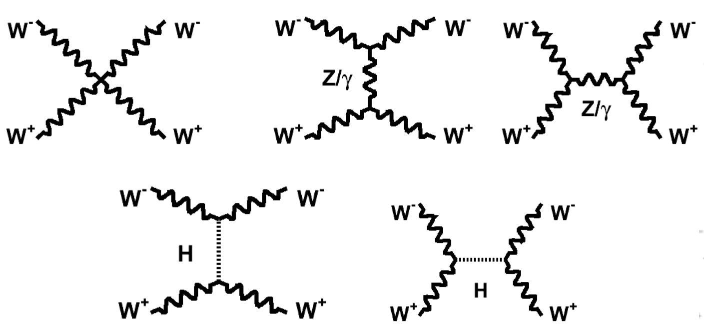
The Higgs Boson

Peter Higgs



- Electroweak Symmetry breaking caused by scalar Higgs field
- vacuum expectation value of the Higgs field $<\Phi> = 246$ GeV/c^2
  - gives mass to the W and Z gauge bosons,
    - $M_W \propto g_W <\Phi>$
  - fermions gain a mass by Yukawa interactions with the Higgs field,
    - $m_f \propto g_f <\Phi>$
  - Higgs boson couplings are proportional to mass
- Higgs boson prevents unitarity violation of WW cross section
  - $\sigma(pp \to WW) > \sigma(pp \to \text{anything})$
    - => illegal!
    - At $\sqrt{s}$=1.4 TeV!





$$A \approx g^2 \frac{E^2}{M_W^2}$$

$$A \approx -g^2 \frac{E^2}{M_W^2}$$

Terms which grow with energy cancel for E >> M_H

This cancellation requires M_H < 800 GeV

The Higgs Boson

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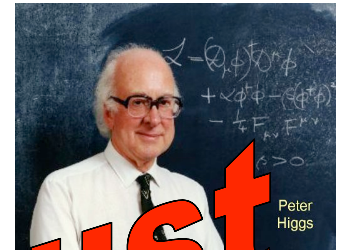
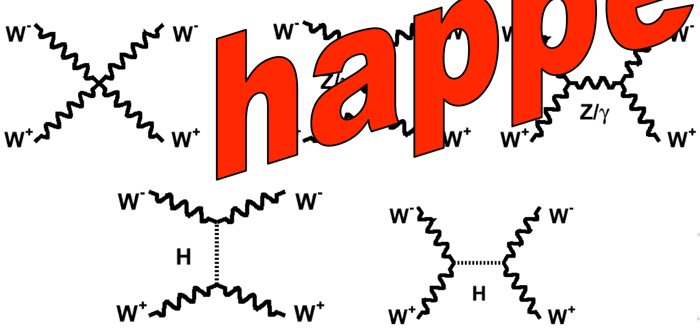
Peter Higgs



Something new must happen at the LHC!



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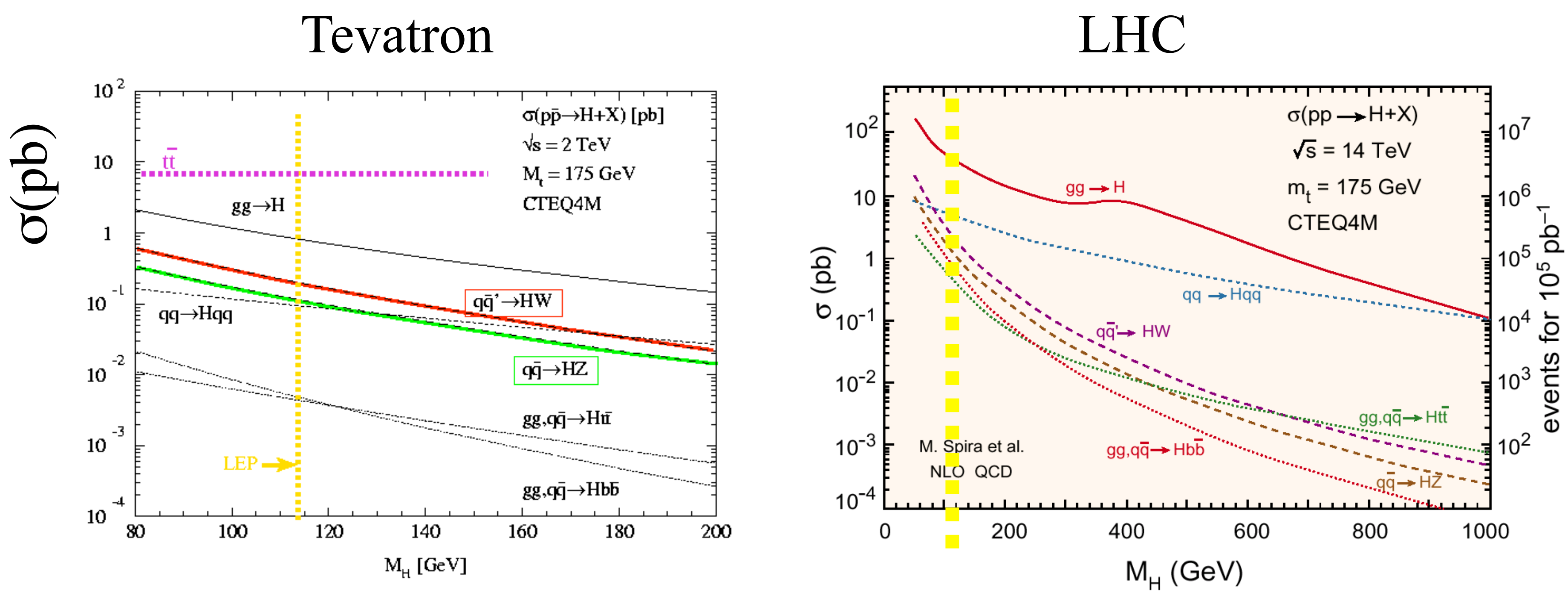
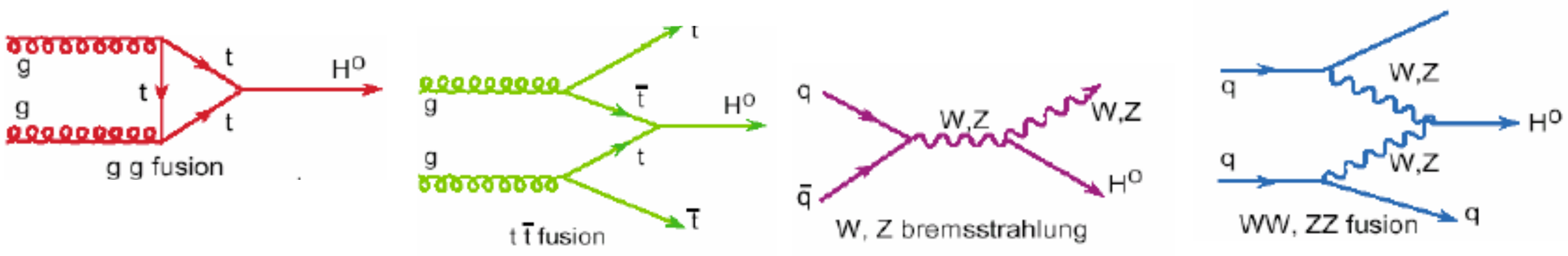
Higgs Production: Tevatron and LHC

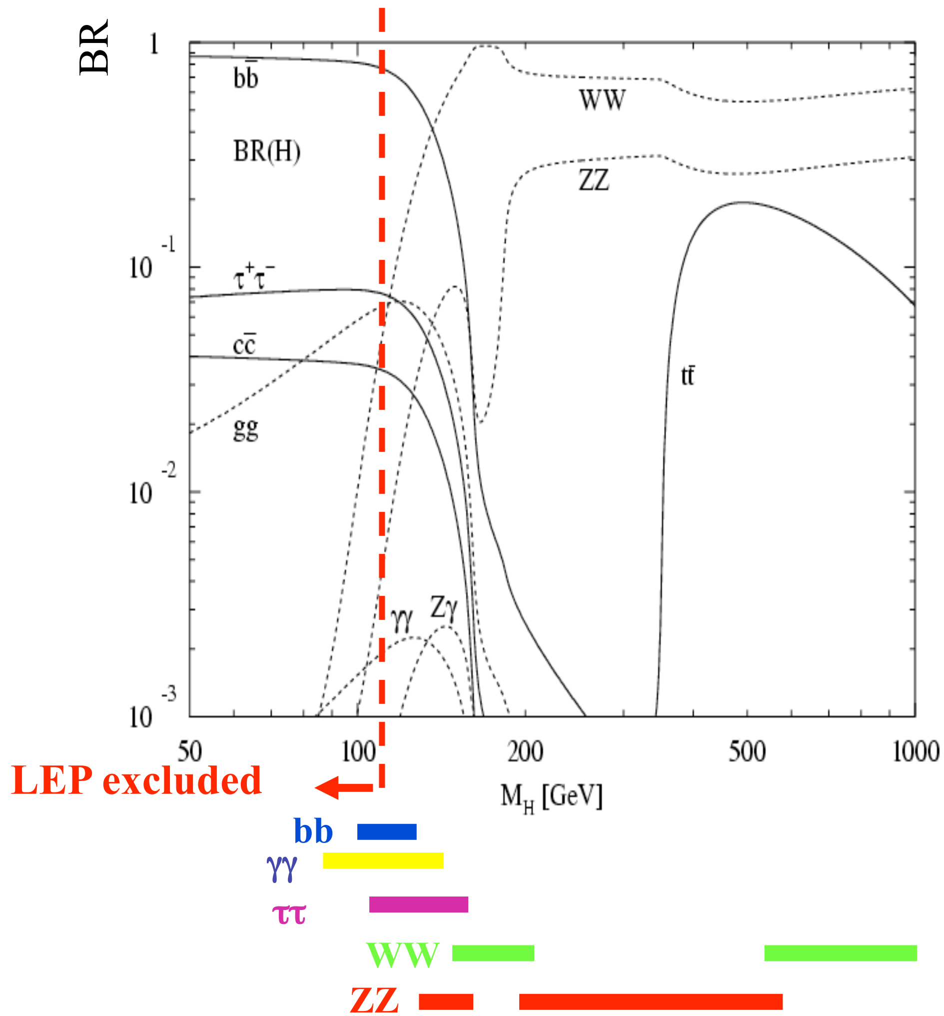




dominant: gg→ H, subdominant: HW, HZ, Hqq

Higgs Boson Decay

- Depends on Mass
- M_H<130 GeV/c^2:
  - $b\bar{b}$ dominant
  - WW and $\tau\tau$ subdominant
  - $\gamma\gamma$ small but useful
- M_H>130 GeV/c^2:
  - WW dominant
  - ZZ cleanest

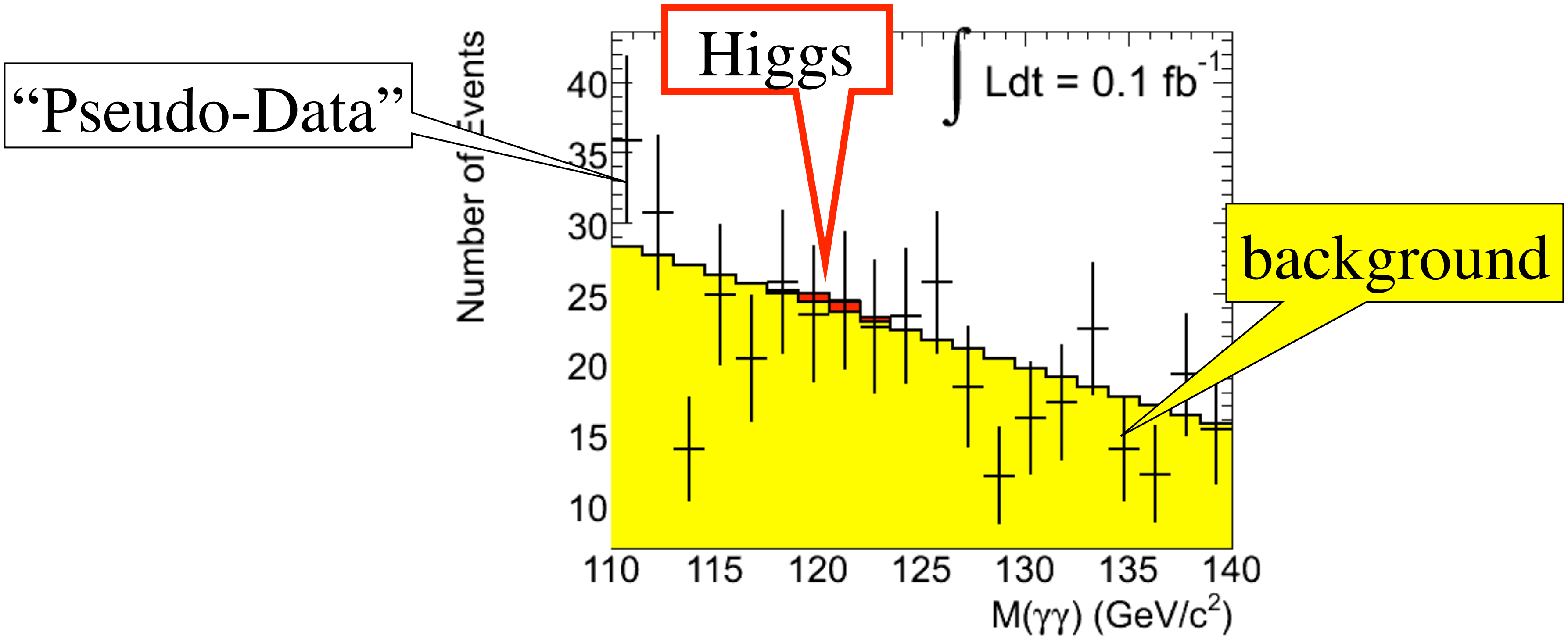


How to make a Discovery

- This is a tricky business!
  - Lot's of complicated statistical tools needed at some level
- But in a nutshell:
  - Need to show that we have a signal that is inconsistent with being background
    - Number of observed data events: N_{Data}
    - Number of estimated background events: N_{Bg}
  - Need number of observed data events to be inconsistent with background fluctuation:
    - Background fluctuates statistically: $\sqrt{N_{Bg}}$
  - Significance: $S/\sqrt{B}=(N_{Data}-N_{Bg})/\sqrt{N_{Bg}}$
    - Require typically 5σ, corresponds to probability of statistical fluctuation of 5.7×10^{-7}
    - Increases with increasing luminosity: $S/\sqrt{B} \sim \sqrt{L}$
    - All a lot more complex with systematic uncertainties…

A signal emerging with time

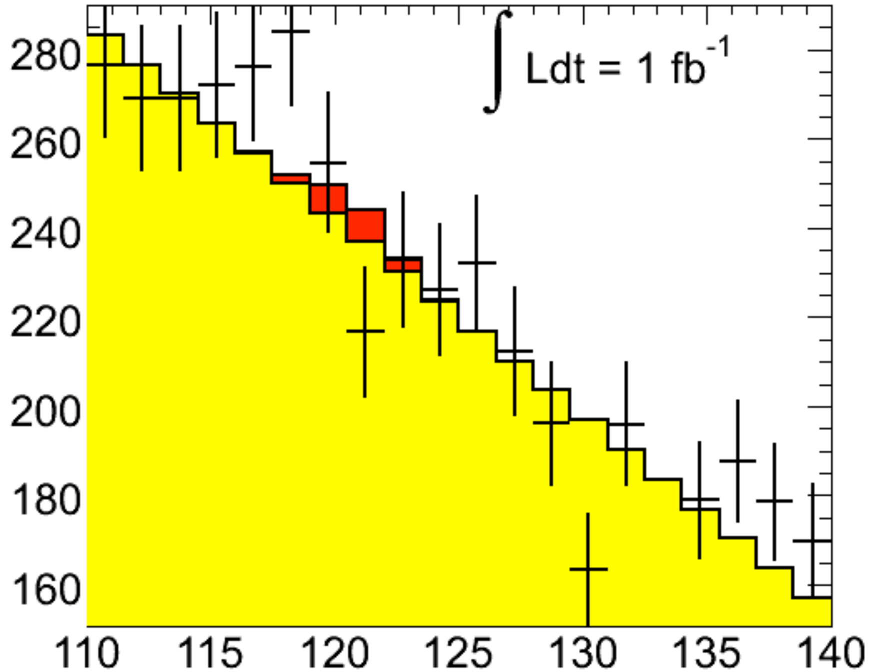
∫Ldt = 0.1 fb^{-1} (year: 2008/2009)



- Expected Events:
  - N_{higgs}~2, $N_{background}$=96 +/- 9.8
  - $S/\sqrt{B}$=0.2
- No sensitivity to signal

A signal emerging with time…

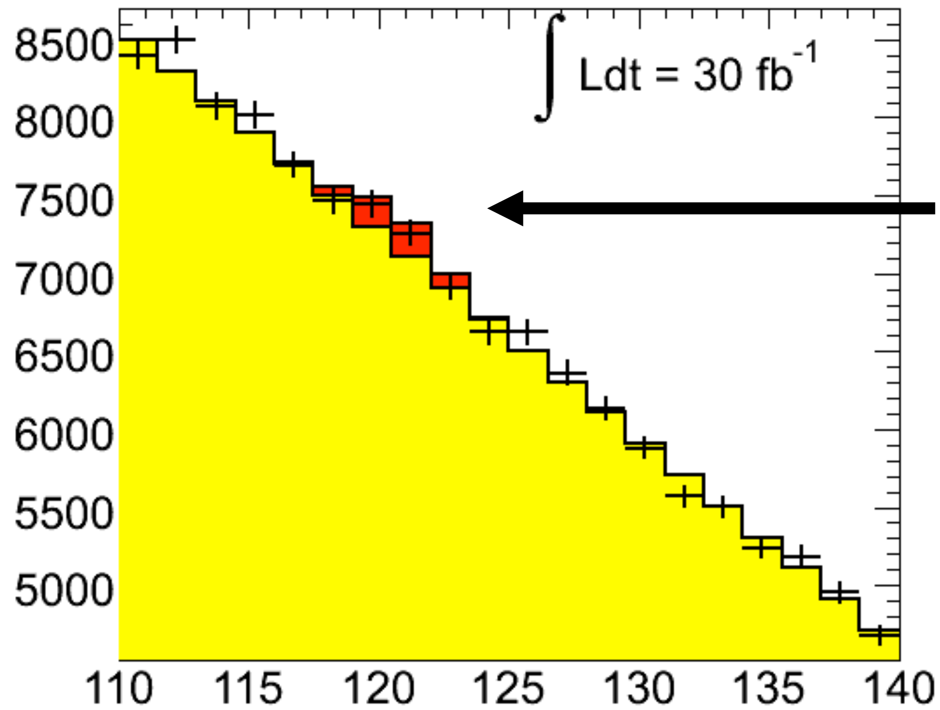
$\int Ldt = 1\ fb^{-1}$ (year: ~2009)



- Expected Events:
  - N_{higgs}~25, $N_{background}$~960 +/- 30
  - $S/\sqrt{B}=0.8$
- Still no sensitivity to signal

There it is!

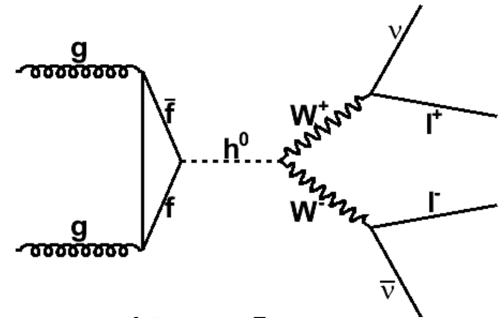
$\int Ldt = 30\ fb^{-1}$ (year: 2011/2012?)



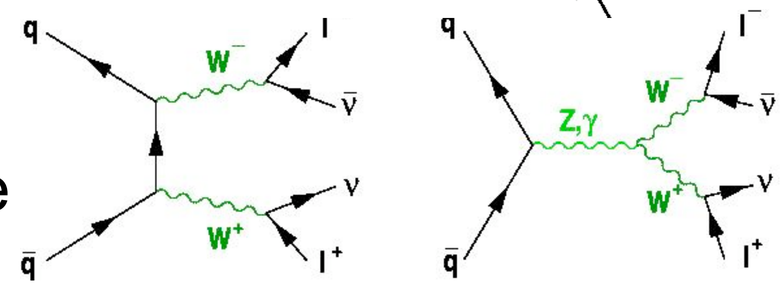
- Expected Events:
  - N_{higgs}~700, $N_{background}$=28700 +/- 170
  - S/√B=4.1
- Got it!!!

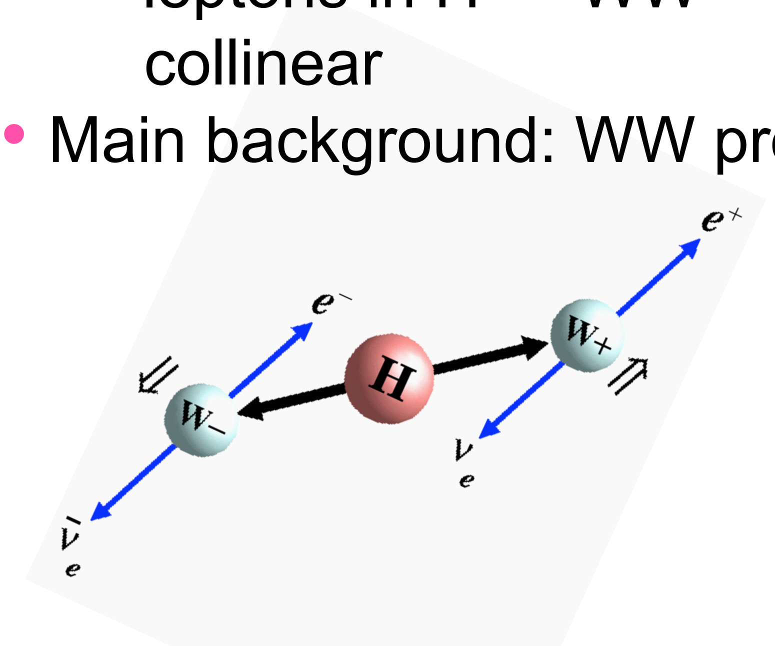
High Mass: m_H>140 GeV

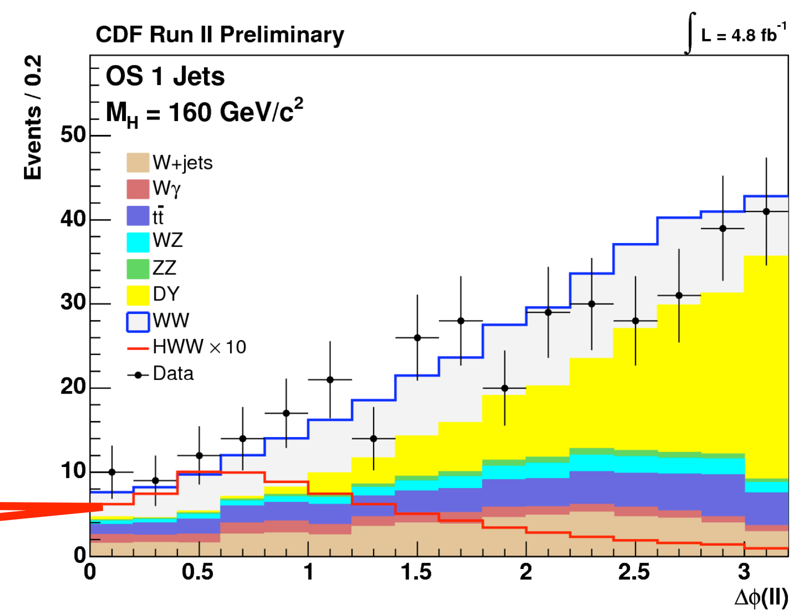
$H \rightarrow WW^{(*)} \rightarrow l^+l^-\nu\bar{\nu}$



- Higgs mass reconstruction impossible due to two neutrinos in final state
- Make use of spin correlations to suppress WW background:
  - Higgs is scalar: spin=0
  - leptons in $H \rightarrow WW^{(*)} \rightarrow l^+l^-\nu\nu$ are collinear
- Main background: WW production



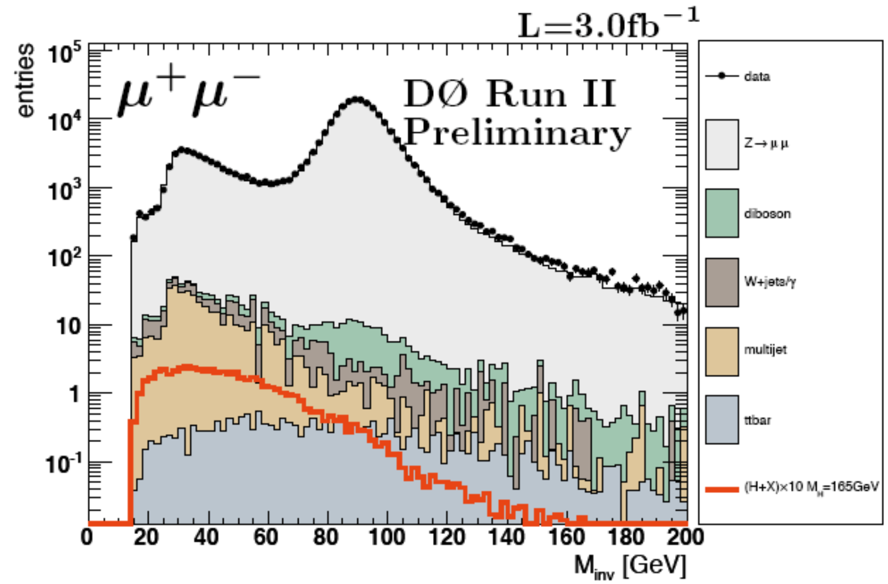


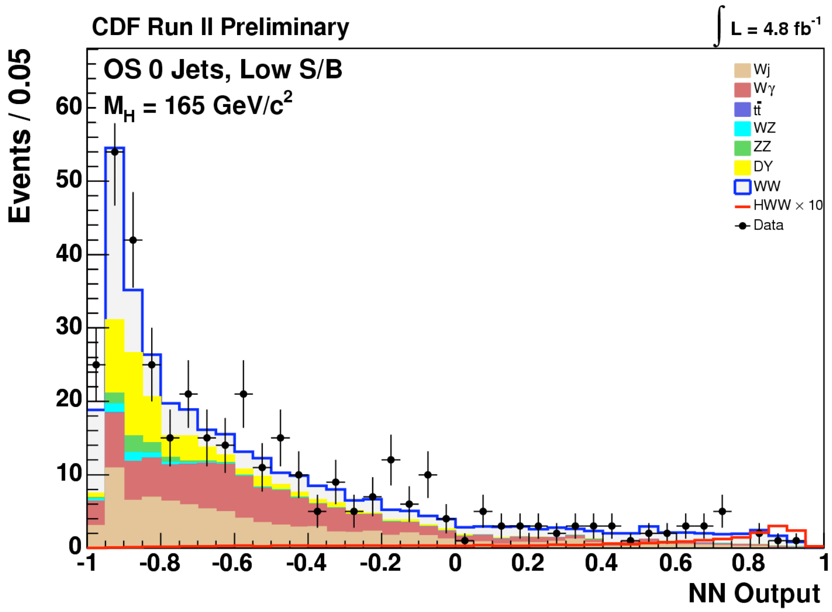


10x 160 GeV Higgs

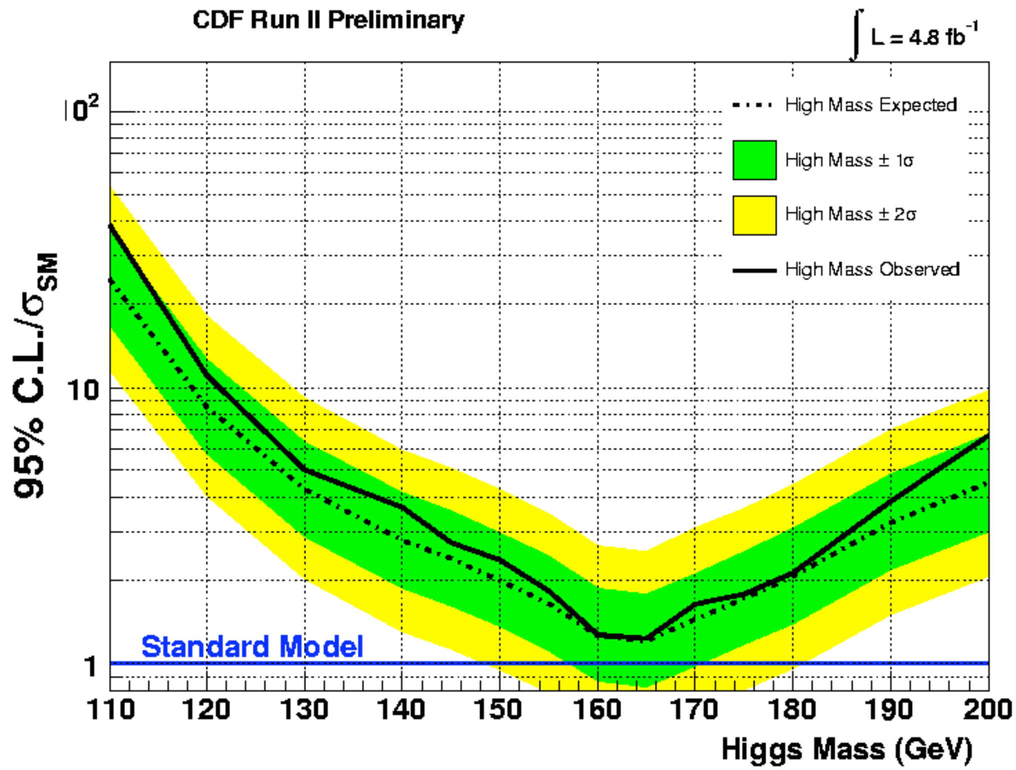
$H \to WW^{(*)} \to l^+l^-\nu\nu$ ($l=e,\mu$)

- **Event selection:**
  - 2 isolated e/μ :
    - p_T > 15, 10 GeV
  - Missing E_T >20 GeV
  - Veto on
    - Z resonance
    - Energetic jets
- **Separate signal from background**
  - Use matrix-element or Neural Network discriminant to denhance sensitivity
- **Main backgrounds**
  - SM WW production
  - Top
  - Drell-Yan
  - Fake leptons
- **No sign of Higgs boson found yet**





Limits on the Higgs boson cross section



- Lack of observation
  - => an upper limit on the Higgs cross section
  - I.e. if the cross section was large we would have seen it!
- Results presented typically as ratio:
  - Experimental limit / theoretical cross section
  - If this hits 1.0 we exclude the Higgs boson at that mass!
- In this example from CDF: a factor 1.3 above SM cross section
  - at M_H=165 GeV/c^2

Tevatron vs LHC for gg → H

m_H	Tevatron	LHC 7 TeV	LHC 10 TeV	LHC 14 TeV
120 GeV	1.1 pb	17 pb	32 pb	55 pb
160 GeV	0.4 pb	9.2 pb	18 pb	33 pb

- Cross sections ~20 times larger at LHC compared to Tevatron
  - Rather strong rise as process is gg initiated
- Backgrounds arise from qq processes
  - Signal/Background better at LHC than Tevatron

Conclusions of 3rd Lecture

- Higgs boson most *wanted* particles
  - LHC must either find it or find something else
- Within the Standard Model constraints from precision electroweak measurements
  - m_W=80.399 ± 0.023 GeV/c^2
  - M_{top}=173.1± 1.3 GeV/c^2
  - m_H between 114 and 157 GeV/c^2